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CESIUM ION PRODUCTION IN A STRONG ION ACCELERATING FIELD

N65-88644

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Abstract

Observations have been made to determine the yield of ions produced at the surface of a heated single crystal of tungsten in a thermionic diode. The cesium condensation temperature was maintained at 470°K, and the surface temperature was varied from 1350°K to 1590°K. The spacing of the diode was varied from 7 microns to 350 microns. The surface area was 1.75 cm^2. The ion yield was observed to follow the Schottky mirror-image theory with a good agreement between the observed slope of the Schottky line and the one computed from theory for the very shortest spacing. At larger spacings the slope of the line was much too great to correspond to the true spacing, therefore, the observed effects are attributed to formation of a plasma near the collector. At very low temperatures the observed currents were many times larger than would have been predicted by the Langmuir-Saha equation, and yet they were in excellent agreement with the random current density that would be anticipated in an isothermal diode operating at the emitter temperature and with a cesium density equal to that used in the experiment. In the high temperature range, ion space-charge effects are strong and yet the zero field ion emission observed was uniformly a factor of approximately 3.7 times greater than that expected from the Langmuir-Saha theory of surface ionization.

FACILITY FORM 602

N65-88644
(ACCESSION NUMBER)

(THRU)

34
(PAGES)

(CODE)

CR-74828
(NASA CR OR TMX OR AD NUMBER)

(CATEGORY)

CESIUM ION PRODUCTION IN A STRONG ION ACCELERATING FIELD[Δ]

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Introduction

The electron emission from a homogeneous surface depends not only on the work-function of the surface and its temperature, but also on the external field caused by the application of potential differences between the emitter and the collector and by space-charge. The space-charge effect can be eliminated by the application of an electron accelerating field strong enough to cancel the space-charge field at the emitting surface. The Schottky[1] theory of work-function reduction by an electron accelerating field has been confirmed by many experiments. This theory depends on the assumption that in the absence of an external field, the force function that acts on an electron at distances greater than approximately 2×10^{-10} m is the mirror-image force function. At 100 times this distance, the intensity of the force is vanishingly small. When an external field is applied to accelerate the electron away from the surface, there is always a distance at which the net value of the motive intensity is zero. This distance becomes small as the field intensity is increased since it is established by the exact cancelling of

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Δ The experimental work presented here was performed under the direction of Mr. R. Breitwieser, Chief, Direct Energy Conversion Branch, NASA, Lewis Research Laboratory. The preparation and presentation of this paper was made possible in part by the U. S. Army Signal Corps, The Air Force Office of Scientific Research, and the Office of Naval Research.

ΔΔ Consultant to NASA Lewis Laboratory and Professor of Physics, Massachusetts Institute of Technology.

Figure Captions

Fig. 1. Mirror-Image Motive Diagrams for Ions and Electrons in Zero Field.

Fig. 2. Motive Diagrams of Fig. 1 on Expanded Scale.

Fig. 3. Schottky Lines Observed at Two Temperatures, $1398^{\circ}K$ and $1401^{\circ}K$, with $T_{Cs} = 470^{\circ}K$.

Fig. 4. Tungsten Work-function Lines as Evaluated from Data of Taylor and Langmuir and J. Houston.

Fig. 5. Schottky Lines at $T = 1399^{\circ}K$, $T_{Cs} = 470^{\circ}K$ at Different Spacings.

Fig. 6. Schottky Lines at $T = 1472^{\circ}K$, $T_{Cs} = 470^{\circ}K$ with Strong Space Charge at the Larger Spacings.

Fig. 7. Schottky Line at $T = 1587^{\circ}K$, $T_{Cs} = 470^{\circ}K$; $W = 8\,\mu$ Showing Very Strong Space Charge Even at Close Spacing.

Fig. 8. Ion Current Densities

Solid line - Close spacing, "zero-field" observations ${}_{+}i_o$.

Dotted line - Random current in Isothermal Diode ${}_{+}i_p$.

Dot-dash line - Ion production with $\alpha = 1$.

Dot-dot-dash line - Ion production by Langmuir-Saha Equation with $\alpha = 2$; ${}_{+}i_{LS}$.

Fig. 9. Ion Current Ratio $({}_{+}i_o/{}_{+}i_p)$ as a Function of T at $T_{Cs} = 470^{\circ}K$. Arrows Show Temperatures for Space Charge Neutrality with $\alpha = 1$ and $\alpha = 2$.

Glossary of Symbols

ΔB_+	Change in ion barrier in eV, (Eq. 4).
$F_{(x)}$	Mirror-image force function, (Eq. 1).
i_a	Atom arrival rate expressed as the equivalent A/cm^2, (Eq. 9).
$_+i_{LS}$	Ion current density given by Langmuir-Saha equation, (Eq. 6).
$_+i_p$	Random current density of ions in an isothermal plasma, (Eq. 12).
k	Boltzmann's constant 1.38×10^{-23} Joule/deg., (Eq. 7).
n	Atom number density in an isothermal diode in atoms/m^3, (Eq. 10).
n_p	Number density of ions in an isothermal diode in ions/m^3, (Eq. 11).
q	Electron or ion charge 1.6×10^{-19} coulomb, (Eq. 1).
S	Slope of Schottky line, (Eq. 8).
T	Emitter temperature in ^oK.
T_{Cs}	Cesium condensation temperature in ^oK.
V	Applied voltage in volts, (Eq. 2).
V_i	Cesium ionization potential 3.89 V_o, (Eq. 9).
$\overline{V}$	Electron-volt equivalent of temperature defined as (kT/q), (Eq. 7).
x	Distance to ion or electron from surface layer of atoms in m, (Eq. 1).
x_e	Critical value of x for ion escape over barrier maximum in m, (Eq. 2).
X_l	Distance from surface layer of atoms to fictious plane of infinite image force, (Eq. 1).
W	True diode spacing, (Table 1).

Glossary continued

W_e	Effective diode spacing, (Eq. 2).
α	Factor in Langmuir-Saha equation taken generally as 2, (Eq. 9).
ϵ_o	Permitrivity of free space, 8.85×10^{-12} coulomb/V . m, (Eq. 1).
ϕ_c	Chart value of the tungsten work-function with cesium coverage in eV, (Fig. 4).
u	Plasma potential in an isothermal diode relative to the Fermi level in eV, (Eq. 10).

the mirror-image field by the external field. It follows that the total change in work-function comes from two effects equal in magnitude. The first is that the actual motive function between the surface and the critical distance of escape is weaker than that in the absence of the field, and a second term results from the fact that no additional work is needed to carry the electron beyond the critical distance. The Schottky theory of the reduction of work-function takes these two facts into consideration and yields an equation which requires a linear relation between the logarithm of the observed current and the square root of the surface field.

In a diode of the type useful for thermionic conversion of heat to electricity both ions and electrons are likely to be present in the inter-electrode space. In this space at distances from homogeneous emitter and collector surfaces greater than approximately 5×10^{-8}m, the average value of the motive function for both the electrons and the ions is the same. Very close to the surfaces the motive functions separate, because mirror-image forces act on individual electrons and ions to accelerate them toward the surface. Thus for an ion to escape from a surface, it must have sufficient kinetic energy in the immediate neighborhood of the surface not to be brought to a stop by its mirror-image potential before it has traveled a sufficient distance for this force to be negligible.

Thermionic emission is observed when sufficient electrons occupy high energy quantum states many atom distances inside the surface. In their random motion some electrons cross the boundary layer of the surface atoms and escape into the interelectrode space if they have sufficient energy. Others with less energy to overcome such barriers that may exist in the motive function outside of the surface are turned back. In general, the energy distribution of the electrons that do escape may be characterized as a Maxwell-Boltzmann distribution having a characteristic temperature precisely equal to that of the emitting surface.

A heated surface in the presence of cesium vapor, for example, may have adsorbed on it many atoms in various vibrational states of motion. In addition there may be a considerable translation of these atoms over the surface as a two-dimensional gas. They nevertheless are in a constant state of vibration relative to the surface governed by some force-function that holds them there. Experiment shows that as more and more atoms get adsorbed on the surface, the average of these forces generally becomes weaker and the average lifetime of the atoms on the surface becomes shorter. In equilibrium the rate of arrival of atoms must equal the rate of evaporation. Under the operating conditions most likely to be of interest in energy conversion diodes, the fraction of the atoms that leave as neutral atoms is very large in comparison with those that leave as positive ions. It is impossible to know the details of the life history of an atom which leaves a heated surface as an ion. During its time of residence between its arrival from a vapor state and its return to the interelectrode space as an ion, its vibration was quantized and its vibrational energy level must have changed very frequently. It may receive energy from the lattice to raise it into a relatively high energy state and on occasion it may return energy to the lattice as it drops from a high-energy state to a lower one. Although these transitions take place in a very random manner with little or no direct coupling in this respect with neighboring adsorbed atoms, it seems reasonable to assume that the probability of finding an atom or an ion in a given quantum state will be largely governed by Maxwell-Boltzmann statistics. An examination of the data of Langmuir and Taylor[2] indicates that within the accuracy of their measurements, the energy distribution of the ions produced at a hot filament surface was one corresponding to the temperature of the surface. Similar studies made by Ionov[3] also serve to establish that the energy distribution is Maxwellian.

With this fact in mind, it is to be expected that the lowering of the barrier, that inhibits the emission of ions, by the application of an external field should cause an increase in the ion yield. Furthermore, since one should anticipate that the mirror-image force would be the dominating one at distances greater than 5×10^{-10} m, the Schottky theory of reduction in barrier height should apply to ions as well as to electrons. Morgulis[4] and Dobretsov[5] seem to have been among the first to point out this field influence as it relates to the production of ions at a heated surface.

It is the purpose of this paper to supply evidence that a diode of extremely close spacing yields ions at the heated emitter surface in such a manner that the current density rises as anticipated by the Schottky mirror-image theory. Experiments carried on at this very close spacing yielded a Schottky slope completely consistent with the spacing and the known temperature. At greater spacing the logarithmic plot yielded good straight lines when not influenced by the retarding effect of ion space-charge. The slope of these lines did not change with spacing, indicating that the surface fields were very much higher than those anticipated in the absence of plasma formation. The evidence seems to indicate that in the immediate neighborhood of the collector, there is very little change in electric field with a change in applied potential, whereas in the immediate neighborhood of the emitter the change in the field is larger by a very considerable factor than would have been present in the absence of the plasma formation effect.

Review of the Schottky Mirror-Image Theory

The basic equations of the Schottky mirror-image theory serve to establish the nature of the motive functions in the immediate neighborhood of the emitter and in the absence of external fields due to space-charge effects or applied potentials. The actual force acting on an electron or an ion and attributed to the mirror-image force decreases with the square of the distance from the surface. The equation for this force function is

$$F(x) = - \frac{q^2}{16\pi \epsilon_o (x + X_1)^2} \quad \text{newtons} \qquad (1)$$

Although the actual force function must be weaker than the mirror-image function when the distance is less than 10^{-10}m, experiment shows that at greater distances the force function is well represented by Eq. (1). If the energy of an electron or an ion at 10^{-7} m from the surface is taken as the reference, the integration of Eq. (1) from any particular location x to infinity provides the means of establishing corresponding motive functions. These are illustrated graphically in Figs. 1 and 2. Here the ordinate represents the motive functions in eV with distance as the abscissa. The dot-dash line is the motive function for electrons which is extended down to and beyond the Fermi level appropriate to a surface with a 3-volt work-function. Permitted electron energies all lie below this line. The motive function for ions is represented by the dash-plus line and permitted energies are above it. To draw the motive function for ions at distances less than 10^{-9}m would depend entirely on speculation, since the experiments to be described apply to sufficiently weak ion-accelerating fields for the minimum critical escape distance to be 6×10^{-9}m.

Figure 1 was drawn to a scale which permitted the display of the Fermi level as well as the various motive functions. Figure 2 has been prepared to display the same motive function expanded by a factor of 10. The distance scales on both figures are the same. Again, the motive functions for the ions and the electrons are represented by the dash-plus line and the dot-dash line in the absence of an applied field. Superimposed on the diagram of Fig. 2 are the motive functions in the presence of an externally applied field of 10^7 V/m. This line is shown as a dashed line. The modifications of the two motive functions are also shown. The modified ion motive function is shown as a solid line and the modified electron motive function is the dotted line. Since ions are free to occupy states on or above the corresponding ion-motive lines, the mirror-image theory of barrier reduction for ion escape indicates that the application of an ion accelerating field of 10^7 v/m permits the escape of ions, normally not escaping at zero field, in the energy band between 0.12 eV and 0 eV. The critical distance for the example illustrated is 6×10^{-9}m from the surface. Weaker external fields have associated with them critical distances which are greater than this value and barriers reduced to a lesser extent when related to the zero field barrier. The critical distance for any particular value of field may be computed by

$$x_c = \left(\frac{q}{16\pi \epsilon_o} \right)^{1/2} \left(\frac{W_e}{V} \right)^{1/2} \qquad (2)$$

In this equation a given applied voltage V divided by an effective spacing W_e is used to express the strength of the surface field in V/m units. Experiment shows that if the actual spacing of the diode is very small in comparison with the mean-free path of the ions or the electrons, the effective spacing equals the actual spacing. For the range in fields used in these experiments, the value of X_1 is so small in comparison with x_c that it is neglected. Equation (2) prepared for numerical calculation is

$$x_c = 1.90 \times 10^{-5} \left(\frac{W_e}{V} \right)^{1/2} \quad \text{m} \qquad (3)$$

The reduction in barrier height with surface field according to the mirror-image theory is expressed in electron volts by

$$\Delta B_{+} = \frac{V}{W_e} \int_{0}^{x_c} dx - \frac{q}{16\pi\epsilon_o} \int_{x_c}^{\infty} \frac{dx}{(x + X_1)^2} \tag{4}$$

This equation, when integrated as indicated, yields the result given by

$$\Delta B_{+} = 2 \left(\frac{q}{16\pi\epsilon_o} \right)^{1/2} \left(\frac{V}{W_e} \right)^{1/2} \tag{5}$$

Equation 5 when prepared for the direct evaluation of the change in barrier height for a field expressed in V/m is

$$\Delta B_{+} = 3.8 \times 10^{-5} \left(\frac{V}{W_e} \right)^{1/2} \tag{6}$$

With a change in barrier height given by Eq. (6), the increase in ion current density may be computed. The current density itself may be related to that for zero field by

$$\log_{10} {}_{+}i_1 = \log_{10} {}_{+}i_o + \frac{1.65 \times 10^{-5}}{W_e^{1/2}} \cdot \frac{V^{1/2}}{\overline{V}} \tag{7}$$

This equation immediately suggests that the logarithm of the observed current density should be plotted as a function of $(V^{1/2}/\overline{V})$. If the Schottky theory applies, the resulting display of experimental data should yield a straight line. The slope of this line establishes the effective spacing and the intercept of the line indicates the zero field ion emission density. The slope defined as S and determined from any two points on the line may be used in the following equation to obtain the effective spacing

$$W_e = \frac{2.72 \times 10^{-10}}{S^2} \quad m \tag{8}$$

Experimental Results

The test vehicle used in these studies was constructed by the Thermo-Electron Engineering Company to provide a diode with a tungsten emitter which is essentially a single crystal of 1.75 cm^2 area with a (110) orientation. The collector in this diode was a polished polycrystalline tungsten surface of the same area. Provision for adjustable spacing was included in the construction, many of the details of which are given in the previous report by Mr. Breitwieser. By careful adjustment it was possible to operate the diode with a spacing between 5 and 10 microns and accurately adjust it to much larger values. The emitter was heated by means of an electron gun designed by R. Breitwieser to give exceptionally uniform heating over the surface. Guard-rings were provided to minimize spurious currents including the elimination of leakage current over the insulating support of the collector.

The circuit arrangement permitted the control of the emitter temperature to a high degree of accuracy and reproducibility to the order of one degree. Currents could be measured accurately from microamperes to 100 amperes. Applied voltages could be controlled and measured over the entire range for these studies from 100 volts negative for the collector as referenced to the emitter to 5 or 10 volts positive as needed. All currents and voltages were measured on an accurately calibrated pen and ink recorder. Complete runs were made within a very few seconds. Recorded data were then tabulated for further analysis. Typical plots of the data are illustrated in Fig. 3. The two lines in this figure apply to results of observations taken at the very close spacing of 7×10^{-6}m and with a deliberate change in the emitter temperature of 3 degrees. All of the factors including the cesium condensation temperature and the collector temperature were maintained constant. It will be noted that the ion yield increases nearly 3 percent per degree as the temperature is changed. Part of this effect is due to the increased work-function of the emitter surface following a change in the total atom population of the surface. The change in temperature itself increases the ion yield when the work-function is considerably lower than the ionization potential of cesium.

The relation between emitter work-function, emitter temperature and cesium temperature is conveniently displayed by means of the lines in Fig. 4. Although these data apply specifically to studies of Taylor and Langmuir[2] and also those of Houston[6], the data obtained in the present test diode are so accurately represented by these lines that this chart is very useful in that it correlates so well the observed data.

The data presented here depend on a series of studies made at a constant cesium temperature of 470°K and a variation in the emitter temperature from 1352°K to 1587°K. Over the lower 100 degrees of this range, no ion space-charge is anticipated since the electron emission expected is well above that needed to neutralize ion space-charge. Over the upper 100 degrees of this range, a stronger and stronger applied field is needed to eliminate the space-charge limitation of the ion production since there are insufficient electrons emitted to accomplish neutralization electronically.

Data shown in Fig. 5 are typical of those obtained in the lower temperature range over which the ion space-charge is neutralized by electrons. The emitter temperature is $1400^{\circ}K$ and the cesium bath temperature $470^{\circ}K$. At the very short spacing of about 7 microns, the Schottky slope obtained is that given by the theory when the surface field is calculated with an effective spacing equal to that of the actual spacing. Although some decrease in slope of the Schottky line is observed as the spacing is increased to 348 microns, the effective spacing did not exceed 11 microns. Over this range of spacing, the zero field ion current is independent of the spacing within the accuracy of the observations, since such a small change in temperature could account for the variations. The failure of the observed points to follow the Schottky line below approximately 2 volts applied was to be expected since the electron current from the emitter to the collector begins to be comparable in magnitude in the range of 1.7 to 2 volts.

Mention needs to be made of the fact that the applied voltage was corrected for the difference in work-function between the emitter and the collector which was sufficiently close to 1 volt to require that $(V - 1)^{1/2}/\overline{V}$ be used in the plots as shown.

Note that the lines that apply to the greater spacing show observed ion currents in excess of those obtained by the simple extrapolation of the lines observed for high ion accelerating voltages. This result is to be attributed to the fact that an electron space-charge sheath exists in the immediate neighborhood of the emitter when the applied voltage is very low and thus gives a higher average surface field to sweep the ions into the space than would be calculated merely on the basis of the electrostatic potential.

The data of Fig. 6 apply to the study made with an emitter temperature at $1472^{\circ}K$ and a cesium temperature of $470^{\circ}K$. Here, except for the very smallest spacing, ion space-charge effects are very evident. Again, at this small spacing the Schottky line slope is close to that expected according to the theory, whereas for the larger spacings, the slope is distinctly greater thus corresponding to an effective spacing considerably less than that of the test diode. Space-charge effects are in evidence with the greater space-charge suppression associated with a greater distance. Figure 7 applies to a study made at a spacing of 80 microns and an emitter temperature of $1587^{\circ}K$, and cesium temperature of $470^{\circ}K$ showed data that followed very closely to the universal space-charge curve[7] whereas the data shown in Fig. 6 do not follow that curve. This is taken as an indication that both electron space charge and ion space charge are influencing the rise in the current with ion accelerating voltage. At the higher temperature the ion excess was sufficient to make the electron contribution negligible.

Interpretation of Experimental Results

The data displayed in Figs. 5, 6, and 7 have been analyzed to determine numerically the effective spacing for comparison with the actual spacing. These results are summarized by Table 1.

TABLE 1

Effective Spacing W_e Determined From Schottky Line Slopes Compared To Actual Spacings W.
$T_{Cs} \approx 470^0K$

(Spacings in microns)

T →	1352^0K	1400^0K	1472^0K	1498^0K	1587^0K
W	W_e	W_e	W_e	W_e	W_e
7$^{\Delta}$	5	6.6	13.4	9	14.7
57	9	10.5	40	ΔΔ	ΔΔ
116	9	10.5	40.5		
232	9	10.9	49		
348		10.5	38.5		

Δ This actual spacing is not known exactly within the limits of 6 to 11 microns.

ΔΔ Strong space-charge effects make the determination of W_e difficult.

It is to be noted that for the very close spacing of approximately 7 microns the effective spacing is sufficiently close to the actual spacing to indicate that plasma effects are not dominating the results. As the spacing is increased the effective spacing increases to some extent but not nearly as much as the actual spacing. The electron mean-free path associated with the estimated cesium density is 300 microns. The ions that pass through cesium vapor can collide and lose kinetic energy rapidly or even effectively lose practically all of their kinetic energy by the process of an exchange collision in which an electron transfers from a slow moving atom to the fast moving ion. Details concerning the probability of such collisions are not known. It is, therefore, assumed that an approximate value for the mean-free path of the ion may be taken as 50 microns.

At very close spacing the electrons generated at the collector surface will be swept across the space in a manner that could be described as "collision-free". At larger spacing, the evidence seems to point toward the formation of a "plasma" condition near the collector. A region of very weak field near the collector that expands with distance could result in an intensification of the field at the emitter surface by the factor of 10 or more as indicated in Table 1.

A second area of interest for interpretation deals with the absolute values of the ion current density at zero field. Superficial considerations would lead one to assume that the Langmuir-Saha equation for ion production at a heated surface of known work-function should set an upper limit to the observed ion current. This equation may be written as follows:

$$+i_{LS} = \frac{i_a}{\alpha\, e^{\frac{V_i - \phi_c}{\overline{V}}} + 1} \qquad (9)$$

In this equation i_a represents the atom arrival rate at the hot surface of work-function ϕ_c. The atom arrival rate, when expressed in units of current density, for a cesium condensation temperature of $470^{\circ}K$, is $1.5\ A/cm^2$. The ionization potential is V_i and the voltage equivalent temperature is $\overline{V}$. Equilibrium statistical theory requires that the constant α has a value of 2. An experimentally determined value of α made by Copley and Phipps[8] gave a value of $\alpha = 1$. Although this deviation from the theoretical value of 2 could be attributed to a temperature coefficient of the surface work-function, this explanation has not been clearly established.

Two other equations of interest were developed by Nottingham[9]. The first is the value of the plasma potential in an isothermal diode with reference to the Fermi level of the surrounding wall. This plasma potential depends only on the number density of the cesium atoms in the space and temperature of the space. It is given in electron volts by

ℓ.c.

$$\mu = \overline{V}\left[25.31 + \frac{3}{4}\ln T + \frac{V_i}{2\overline{V}} - \frac{1}{2}\ln n\right] \qquad (10)$$

Numerical values are obtained from this equation when the number density of cesium atoms is expressed as the number per cubic meter.

The concentration of ions in the isothermal space may be calculated by

$$\ln {}_{+}n_p = 24.62 + \frac{3}{4}\ln T - \frac{V_i}{2\overline{V}} + \frac{1}{2}\ln n \qquad (11)$$

This equation is exact only when the fractional ionization is very small. With the ion concentration known, it is possible to compute the random current of ions in the plasma space. This current is defined in terms of the number of ions that cross any boundary in a particular direction per unit area in unit time and expressed in A/m^2. The equation for the random current is

$$\ln {}_{+}i_p = -17.51 + \frac{5}{4}\ln T - \frac{V_i}{2\overline{V}} + \frac{1}{2}\ln n \qquad (12)$$

With the help of these equations and also Fig. 4, the numerical data in Table 2 were prepared.

TABLE 2

Comparisons Between Experiment and Theory

T	T/T_{Cs}	ϕ_c	μ	$_+i_p$	$_+i_{LS}$	$_+i_o$	$_+i_o/_+i_p$	$_+i_o/_+i_{LS}$
1352	2.88	2.42	2.71	3.13×10^{-5}	2.42×10^{-6}	3.1×10^{-5}	.99	12.8
1375	2.93	2.50	2.72	4.22	5.8×10^{-6}	4.5	1.07	7.8
1400	2.98	2.58	2.74	5.88	1.45×10^{-5}	6.8	1.15	4.7
1400	2.98	2.58	2.74	5.88	1.45×10^{-5}	4.3×10^{-5}	.73	3.0
1421	3.02	2.64	2.76	7.71	2.70	1.2×10^{-4}	1.55	4.4
1442	3.07	2.70	2.78	9.9×10^{-5}	5.0	1.93	1.95	3.9
1460	3.11	2.75	2.79	1.28×10^{-4}	9.4×10^{-5}	2.7	2.1	2.9
1472	3.13	2.79	2.80	1.4	1.3×10^{-4}	4.4	3.1	3.4
1480	3.15	2.81	2.80	1.54	1.5	10.4	6.7	7.0
1480	3.15	2.81	2.80	1.54	1.5	8.6$^{\Delta}$	5.6	5.7
1498	3.19	2.86	2.81	1.81	2.8×10^{-2}	12.2×10^{-4}	6.7	4.3
1587	3.38	3.14	2.88	4.8	3.3×10^{-3}	12×10^{-3}	25	3.6
1587	3.38	3.14	2.88	4.8	$\Delta\Delta$	12.6×10^{-3}	26	3.8

Δ From data at W = 57 microns

$\Delta\Delta$ Obtained from universal space-charge analysis

Definitions: ϕ_c = chart value of work-function from Fig. 4 in eV.

μ = isothermal plasma potential in eV (Eq. 10).

$_+i_p$ = random ion current density in an isothermal diode in A/cm^2 (Eq. 12).

$_+i_{LS}$ = computed Langmuir-Saha ion production (Eq. 9).

$_+i_o$ = observed ion current density at close spacing.

The emitter work-function,as read from the chart of Fig. 4 at the corresponding emitter temperature listed in column 1, is found under the heading ϕ_c. It is of interest to compare this with the plasma potential in the next column. Over the range of temperature between 1352^{o}K and 1472^{o}K the plasma potential is more negative with respect to the Fermi level than the surface potential. This indicates a condition which is theoretically "electron-rich" and there should be no ion space charge at the emitter even at zero field. Over the higher range in temperature, the plasma potential is less negative than the surface potential and an ion space charge situation should be present. The computed isothermal random current density expressed in A/cm^2 is recorded under $_+i_p$. This current density was calculated by Eq. 12. In the next column the Langmuir-Saha current density is computed according to Eq. 9 with $\alpha \approx 2$. Under the column headed $_+i_o$ the observed zero-field current densities are listed. All of these apply to the very close spacing with the exception of one, identified by its footnote applicable to 1480^{o}K. A comparison of values shows the close correlation between the observed current density and the random current density over the low-temperature range, and the very poor correlation between the observed current density and the Langmuir-Saha current density over this range. In the high-temperature range the observed currents are significantly larger than the random currents and between 3 and 4 times the computed Langmuir-Saha current if one uses $\alpha \approx 2$. This discrepancy is reduced by a factor of 2 if α is 1.

It is of interest to display this information in graphical form. The curves in Figs. 8 and 9 have been prepared for this purpose. In Fig. 8 there are three theoretical curves. The dotted line represents the random current computed for the isothermal diode characterized by the temperature T and a cesium condensation temperature of $470^{\circ}K$. The steeper line shown by a dash with 2 dots represents the variation in the production rate of ions with temperature as computed by the Langmuir-Saha equation $\alpha = 2$ when work-functions are taken from Fig. 4. The single dot-dash line is computed in the same manner with $\alpha = 1$. Points determined by experiment and the smooth curve, which represents them within experimental accuracy, is shown by the solid line. Note that the intersection of the Langmuir-Saha line and the isothermal random current line comes at $1478^{\circ}K$. This temperature corresponds to the theoretical value for exact neutralization between the emitted electrons and the ion production. The intersection of the $\alpha = 1$ line comes at $1443^{\circ}K$.

The data recorded under the heading $({}_{+}i_{o}/{}_{+}i_{p})$ are plotted in Fig. 9. Over the range of temperatures below $1440^{\circ}K$ the current ratios observed seem to be very close to unity. Beginning at about $1440^{\circ}K$ a noticeable rise in observed current over that of the isothermal diode takes place. The temperatures mentioned above for the $\alpha = 1$ and $\alpha = 2$ intersections are identified by the arrows in this figure.

Conclusions

The evidence presented here supportsthe following conclusions.

1. The Schottky mirror-image theory can account for the rise in ion yield as a function of surface field for very short spacing.

2. For spacings larger than the estimated ion free-path, the Schottky slope seems to be independent of the spacing.

3. Ion space-charge effects are not noticeable at temperatures below 1440°K.

4. About 1460°K ion space-charge effects are in evidence and at the very high temperature of 1587°K the variation in the ion emission with applied potential is well represented by the universal space-charge curve.

5. In the low-temperature range the ion current observed is close to that computed for the isothermal diode. In the high-temperature range the observed currents rise with temperature as expected from the Langmuir-Saha equation with the current density at least 3 times that computed.

Some of these unexpected results could possibly be explained by temperature and work-function inhomogeneity. Further studies hope to evaluate this factor.

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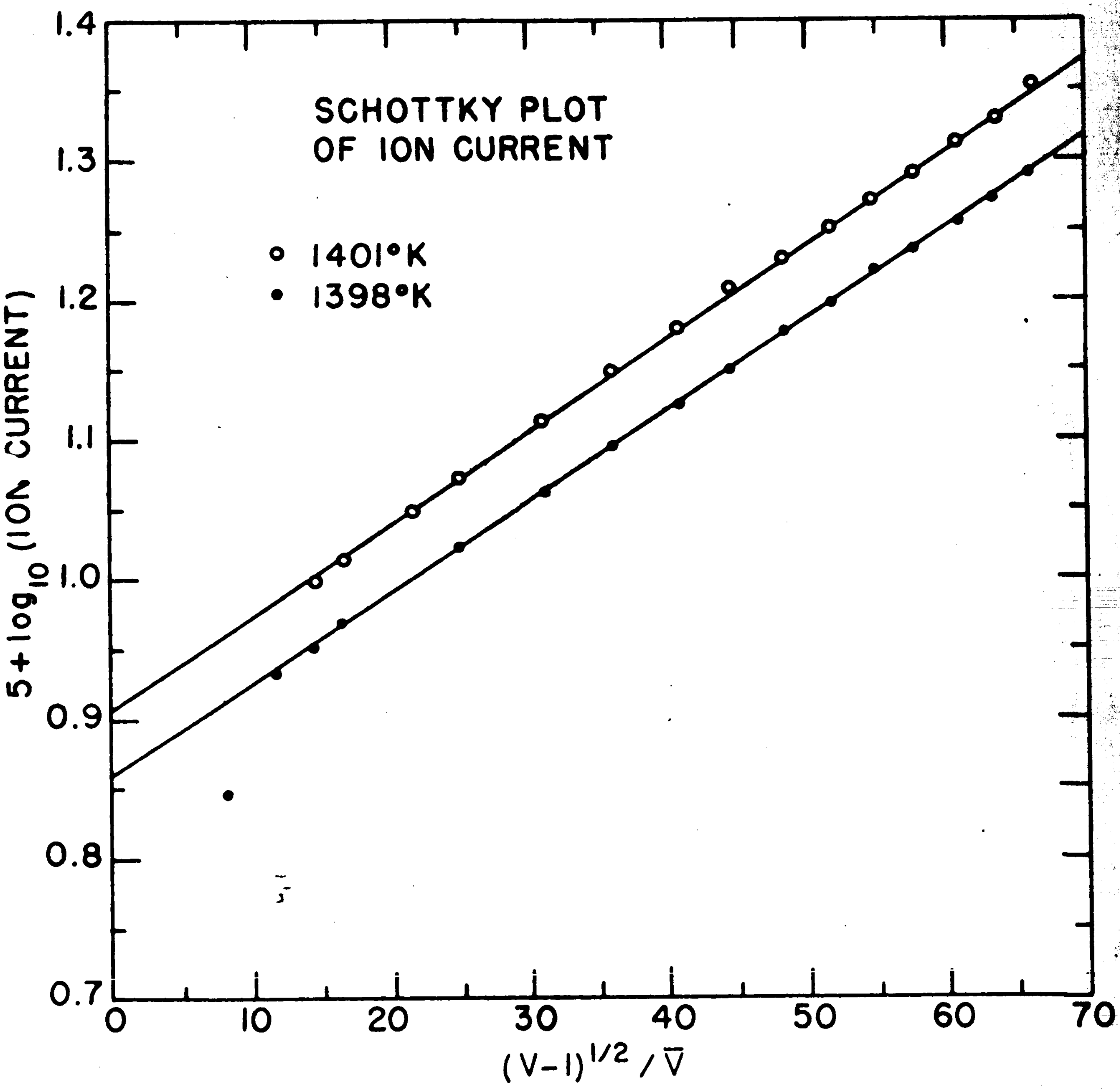

SCHOTTKY PLOT
OF ION CURRENT
○ 1401°K
● 1398°K
5+log10(ION CURRENT)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0
10
20
30
40
50
60
70
(V-1)^1/2 / V̄

FIGURE 3

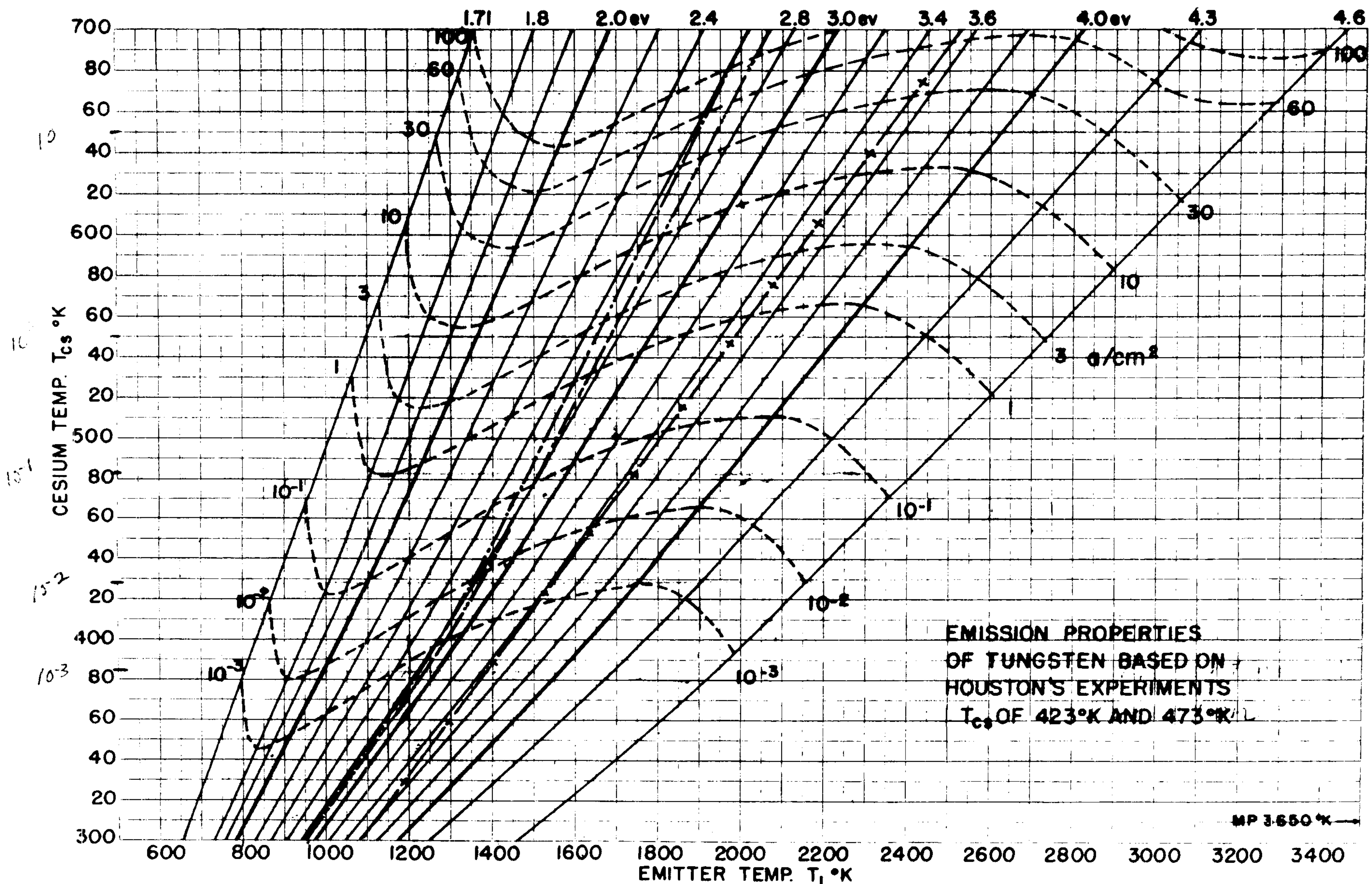
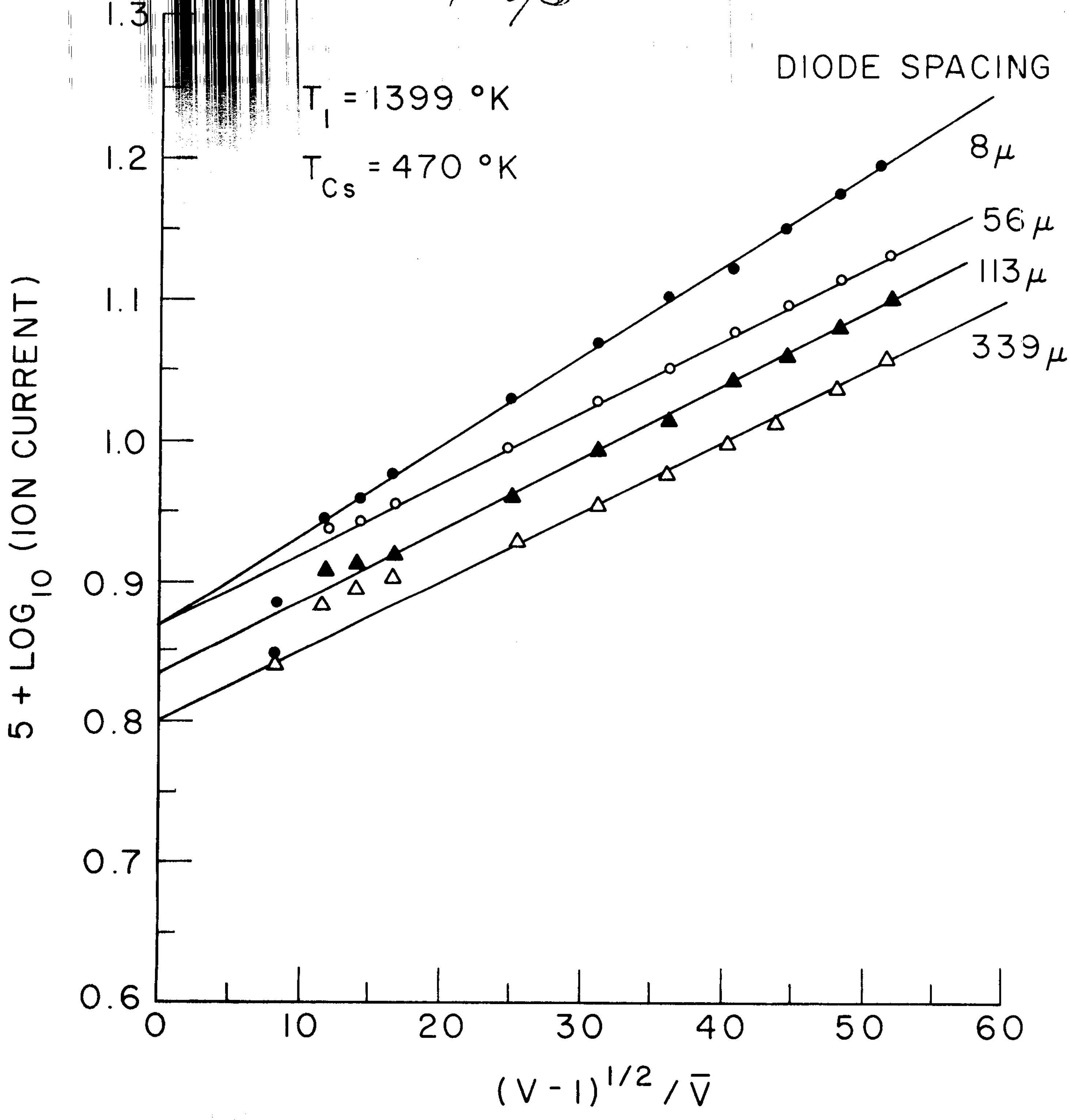


Figure 4. Emission Properties of Tungsten Based on Houston's Experiments, T_{Cs} of 423°K and 473°K

Fig 95



DIODE SPACING
T_1 = 1399 °K
T_{Cs} = 470 °K
8 μ
56 μ
113 μ
339 μ
5 + LOG_{10} (ION CURRENT)
$(V-1)^{1/2}/\bar{V}$
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
0
10
20
30
40
50
60

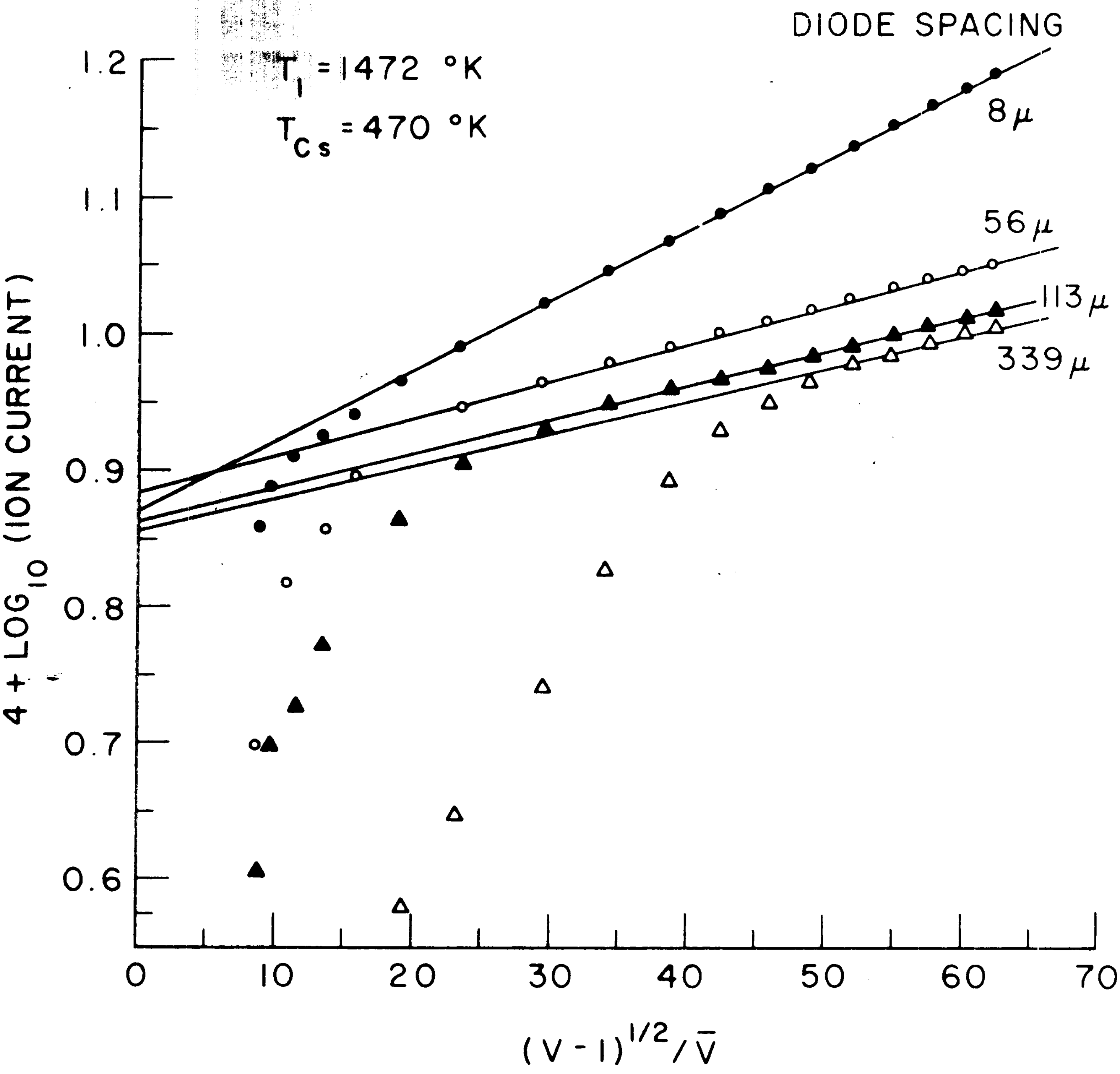
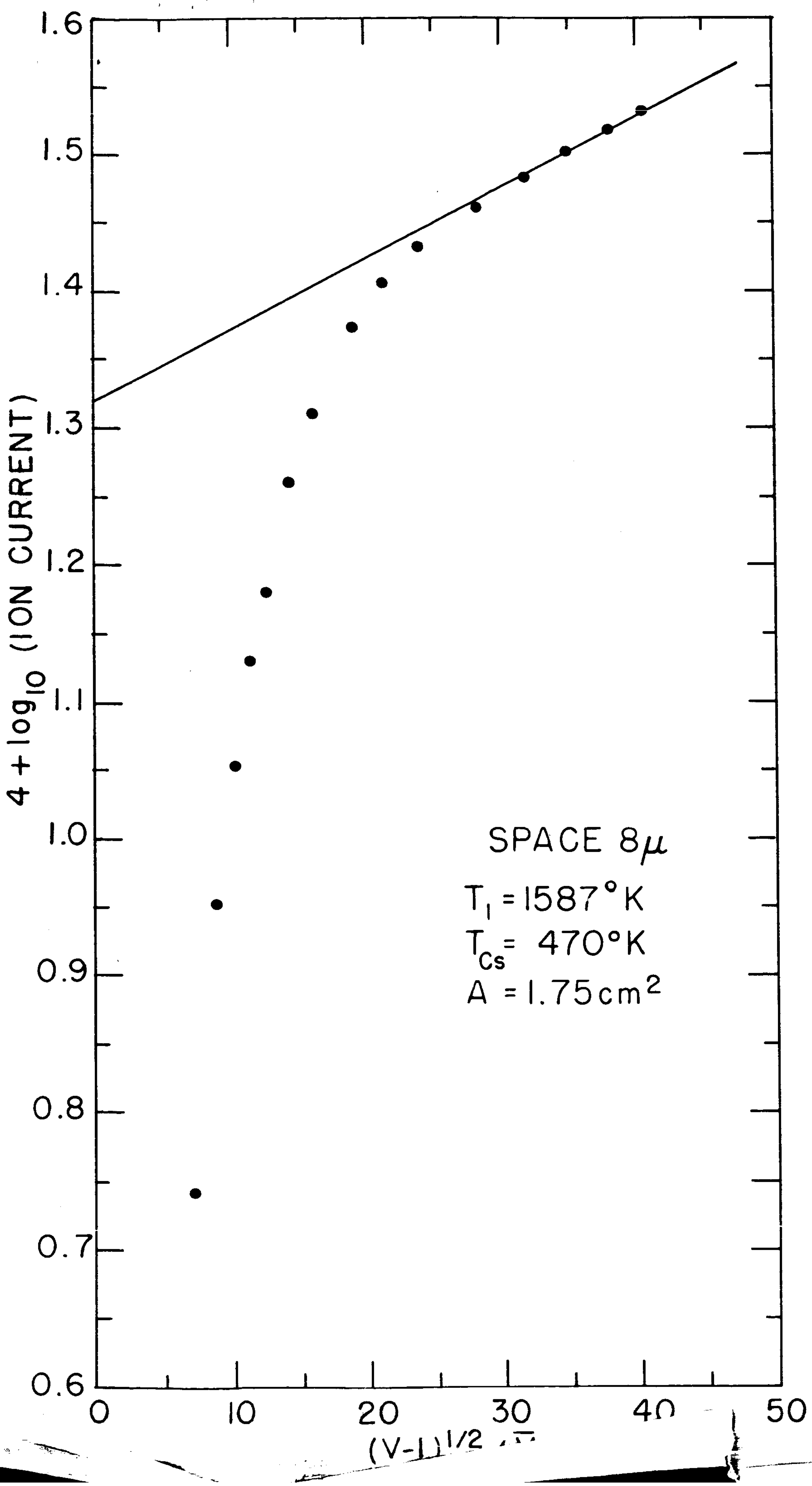
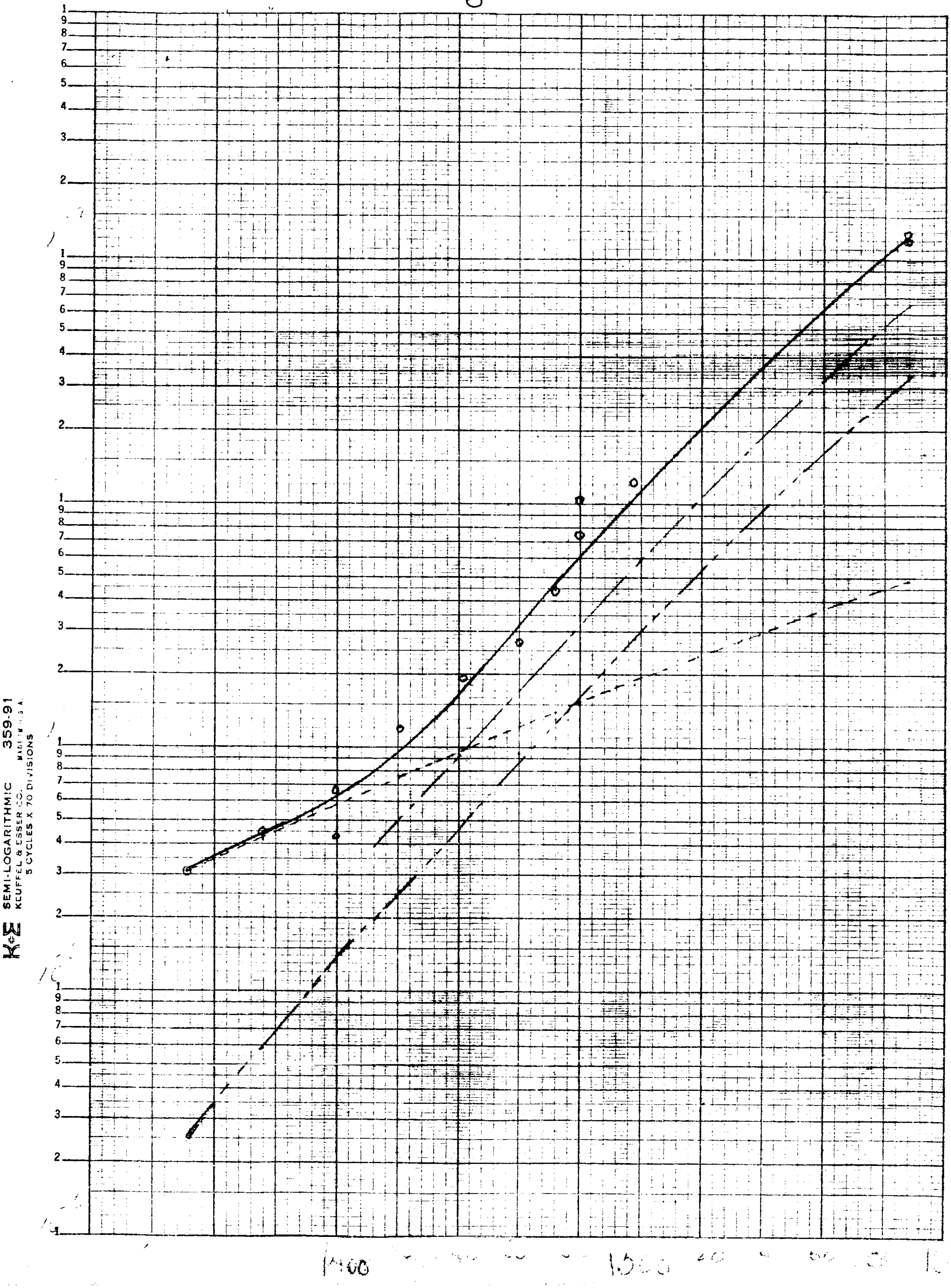

DIODE SPACING
T_1 = 1472 °K
T_{Cs} = 470 °K
8 μ
56 μ
113 μ
339 μ
4 + LOG10 (ION CURRENT)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0
10
20
30
40
50
60
70
$(V-1)^{1/2}/\bar{V}$

FIG 6



SPACE 8μ
T1 = 1587°K
TCs = 470°K
A = 1.75 cm²
4 + log10 (ION CURRENT)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0
10
20
30
40
50

8



K&E SEMI-LOGARITHMIC 359-91
KEUFFEL & ESSER CO.
5 CYCLES X 70 DIVISIONS
1400
1500

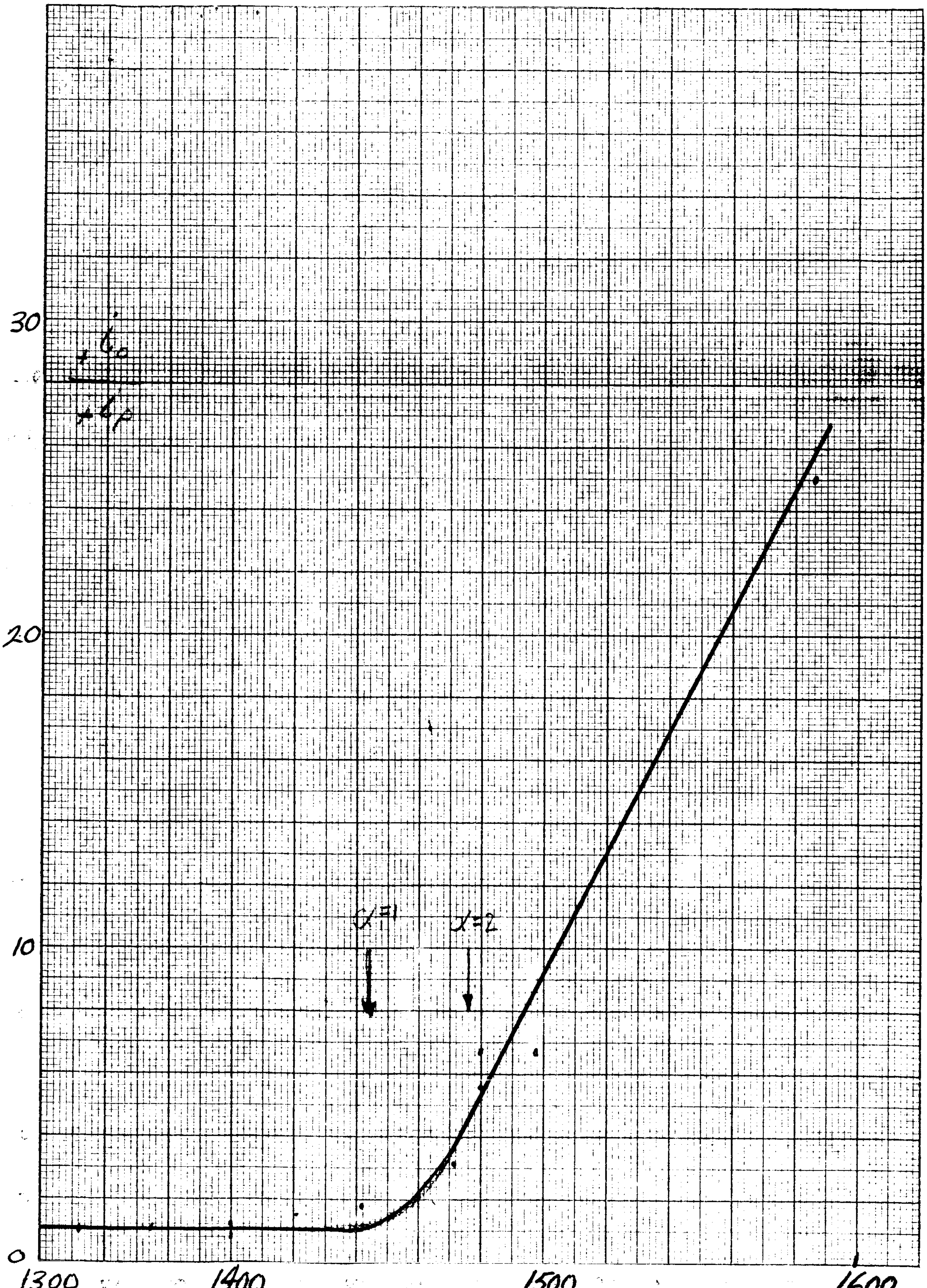


FIG 9